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CRITERION OF THE INSTABILITY OF AN ARBITRARY SYSTEM OF DEFLAGRATION IN THE COMBUSTION CHAMBER OF A ROCKET ENGINE WITH SUCCESSIVE AUTOIGNITION OF THE FUEL

by

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EDITED TRANSLATION

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By: S. K. Aslanov

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ABSTRACT : Based on a previous analysis by the author (Kriteriy neustoychivosti razvitoy deflagratsii i analogiya protsessa sgoraniya v detonatsionnoy volne i v raketnom dvigatele. IVUZ, "Aviatsionnaya tekhnika," No. 1, 1966.), the following criterion was derived for combustion stability in a liquid rocket engine:

$$M_1 > M_{1\,cr} = \frac{1+\sqrt{\alpha\frac{x_1}{x_2}}}{(\alpha-1)m},$$

where M_1 is the Mach number of the fuel-oxidizer gas mixture; M_{1cr} is the critical Mach number of the gas mixture; x_1, x_2 are the specific heat ratios of the fresh gas mixture and combustion products, respectively; and α is the gas velocity ratio. As an example, calculations were made for gasoline based on heptane parameters. The value of M_{1cr} for gasoline was found to be 0.12. Since under real conditions in a rocket motor M_1 is larger than 0.12, internal stability of the combustion regime would be ensured.
Orig. art. has: 6 formulas. English translation: 4 pages.

* Transliterated Title - cont.-TOPLIVA

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CRITERION OF THE INSTABILITY OF AN ARBITRARY SYSTEM OF DEFLAGRATION IN THE COMBUSTION CHAMBER OF A ROCKET ENGINE WITH SUCCESSIVE AUTOIGNITION OF THE FUEL

S. K. Aslanov

In the work [1] there is considered the problem of the persistence of small distrubances in the process of deflagration of a compressed fuel mixture in a system of induction which is characteristic for the heat-stressed combustion chambers of rocket engines with the predominant mechanism of successive autoignition of the mixed and heated components of the fuel. In this situation onto the basic stationary flow directed along the axis x there were imposed gas-dynamic disturbances of the kind const·exp $(k\gamma x + iky \cdot i\omega t)$ limited over great distances from the flame. As a result of satisfying the law of continuity of the flows of the mass, the impulse, and the energy in passing through the flame, and also the conditions imposed on these disturbance of the kinetic chemical reaction there was obtained in [1] an equation for determining the natural number of the given problem

$$
\begin{gathered}
(\alpha-1)\left[\frac{z}{\alpha\gamma_1}+\varphi_1\left(1+\frac{z}{\alpha\gamma_1}\right)-DM_1^2\right]\left[\frac{1}{B}\,\frac{z}{\alpha}(M_2^2-1)+\right.\\
\left.+2+(\varkappa_2-1)M_2^2\right]+(2-\alpha)\frac{z}{\alpha\gamma_1}+\varphi_1\left[1+(2-\alpha)\frac{z}{\alpha\gamma_1}\right]-\\
-\left[D+(\alpha-1)m\frac{z}{\alpha\gamma_1}\right]M_1^2+\frac{1-M_2^2}{B\gamma_1}\left(1-\frac{z^2}{\alpha^2}\right)\times\\
\times\left[\varphi_1\left(2-\alpha+\frac{z}{\gamma_1}\right)-(\alpha-1)mM_1^2\right]=0,
\end{gathered}
\tag{1}
$$

$$B=\frac{z}{\alpha}\mp\sqrt{1-M_2^2+\frac{z^2}{\alpha^2}M_2^2}, \quad \frac{1}{\varphi_1}=1+\frac{z}{\gamma_1},$$

$$D=\frac{1}{\varphi_1}+(\alpha-1)m\frac{z}{\alpha\gamma_1},$$

$$m=\varkappa_1 Q+(\varkappa_1-1)N, \; Q=\frac{\partial \ln \tau}{\partial \ln p}, \quad N=\frac{\partial \ln \tau}{\partial \ln T} \text{ with } P = P_1, \; T_1 = T_2,$$

$$\alpha=\frac{V_2}{V_1}=\frac{\rho_1}{\rho_2}>1, \quad z=-\frac{i\omega}{kV_1},$$

$$(1-M_1^2)\gamma_1=zM_1^2\pm\sqrt{1-M_1^2+zM_1^2},$$

$$(1-M_2^2)\gamma_2=\frac{z}{\alpha}M_2^2\pm\sqrt{1-M_2^2+\frac{z}{\alpha^2}M_2^2},$$

where $\eta(p, T)$ is the rate of the chemical reaction, k is the wave number, and P, ρ, V, T, M, κ are, respectively, pressure, density, speed, temperature, Mach number, and ratio of heat capacity.

The indices (subscripts and superscripts) 1 and 2, signify, respectively, the original mixture and the products of the burning, and the symbols in B and γ_2 are opposite.

The selection of the branches γ_1 and γ_2 is accomplished by the indicated condition of the limitedness of the disturbances $\mathrm{Re}\gamma_1 \geq 0$, $\mathrm{Re}\gamma_2 \leq 0$, from which for the actual z, in particular, there follows the upper sign with γ_1 and the lower with γ_2 (in the case of B). The latter, in turn, flow from the conformity to rule of the possible systems of deflagrations $M_1 < 1$, $M_2 \leq 1$. Further, we investigated in detail the limit cases of the completeness of the development of the Jouguet deflagration ($M_2 = 1$) [1] and in [2] and of the slow burning ($M_2 \ll 1$). It turns out that the first system for the physically real condition is inwardly unstable, and the second always stable.

An analysis of the characteristic equation (1) of the problem under consideration will be derived for the arbitrary system of deflagration $0 < M_2 < 1$, so that it is possible to obtain a sufficient criterion controlling the transition of the stable form of burning to the unstable. For this purpose, having designated the left side of the equation (1) f(z) we explain its behavior in the region $z > 0$.

With $z \to +\infty$

$$\gamma_1 = \frac{zM_1}{1-M_1}, \quad \gamma_2 = -\frac{z}{\alpha}\frac{M_2}{M_2+1}, \quad B = \frac{z}{\alpha}(1+M_2),$$
$$\varphi_1 = M_1,$$

$$f(+\infty) = \frac{1-M_1}{M_1}[(1+M_1)D_0 - 1 - M_1M_2 - (\alpha-1)mM_1^2D_0],$$

$$D_0 = 1 + M_2 + \frac{\alpha-1}{\alpha}(\varkappa_2 - 1)M_2^2,$$

hence for

$$(\alpha-1)mM_1^2 > 1 + M_1 - \frac{1+M_1M_2}{D_0} = A_1, \tag{2}$$

$f(+\infty) < 0$, in the contrary case, $f(+\infty) > 0$.

With $z = 0$

$$\gamma_1 = \frac{1}{1-M_1^2}, \quad \gamma_2 = -\frac{1}{\sqrt{1-M_2^2}}, \quad B = \sqrt{1-M_2^2}, \quad \varphi_1 = 1,$$

$$f(0) = (1-M_1^2)\Big\{1 + (\alpha-1)[2 + (\varkappa_2-1)M_2^2] + \\ + \sqrt{\frac{1-M_2^2}{1-M_1^2}}[2 - \sigma - (\alpha-1)mM_1^2]\Big\}.$$

hence for

$$(\alpha - 1)\, mM_1^2 < 2 - \alpha + \sqrt{\frac{1 - M_1^4}{1 - M_2^4}}\{1 + (\alpha - 1)[2 + (\varkappa_2 - 1) M_2^2]\} = A_2 \qquad (3)$$

$f(0) > 0$, in the opposite case, $f(0) < 0$. And thus one can show that $A_1 < A_2$.

In fact, by using the law of the preservation of the impulse $P_1 + \rho_1 V_1^2 = P_2 + \rho_2 V_2^2$ and $\alpha > 1$, we see that $M_1 < M_2$. Therefore

$$A_1 - A_2 < M_1 - \alpha - \frac{1 + M_1 M_2}{D_0} - (\alpha - 1)(\varkappa_2 - 1) M_2^2 < 0.$$

Consequently the fulfilling of the condition

$$(1 + M_1)\left\{1 - \frac{1 + M_1 M_2}{D_0 (1 + M_1)}\right\} < (\alpha - 1)\, m_1 M_1^2 <$$

$$< 2 - \alpha + \sqrt{\frac{1 - M_1^4}{1 - M_2^4}}\{1 + (\alpha - 1)[2 + (\varkappa_2 - 1) M_2^2]\} \qquad (4)$$

definitely assures at least one positive root $z > 0$ of the equation (1) $f(z) = 0$. In other words the inequality (4) serves as a sufficient criterion of the instability of the process of burning with the arbitrary system of weak deflagration. In the particular case of the Houguet system ($M_2 = 1$) (4) becomes the criterion obtained in [1]:

$$\frac{(\alpha - 1)\, m M_1^2}{(1 + M_1)\left(1 - \frac{1}{D_0}\right)} > 1.$$

In the case of small M_1 and M_2 by disregarding the terms of the second degree in accordance with the Mach number, we find form (4):

$$\frac{\alpha - 1}{M_1 + M_2} > \frac{(\alpha - 1)\, m M_1}{1 + \frac{M_2}{M_1}} > 1. \qquad (5)$$

The expression M_2/M_1 is computed from the law of the preservation of the impulse in the form:

$$\left(\frac{M_2}{M_1}\right)^2 = \frac{\alpha \frac{\varkappa_1}{\varkappa_2}}{1 - \varkappa_1 M_1^2 (\alpha - 1)} \propto \alpha \frac{\varkappa_1}{\varkappa_2}.$$

The left side of the inequality (5) represents considerable magnitude at the small M_1, M_2, so that actually the criterion of the instability with precision to the linear terms in accordance with the Mach number is expressed in the form:

$$\frac{(\alpha - 1)\, m M_1}{1 + \sqrt{\alpha \frac{\varkappa_1}{\varkappa_2}}} > 1.$$

Hence there is found the critical Mach number of the rate of the burning, at which the deflagration process in the chamber of the rocket engine loses the inner stability with relation to the small gas-dynamic disturbances

$$M_1 > M_{1\,\text{крит}} = \frac{1 + \sqrt{\alpha \frac{\varkappa_1}{\varkappa_2}}}{(\alpha - 1)\, m}. \qquad (6)$$

The latter signifies that in the limiting case of $M_1 \to 0$ (incompressible fluid) the slow burning in the system of induction will be stable in accordance with the deductions in [2].

If one disregards the dependence of the rate of the chemical reaction on the pressure and takes the dependence on the temperature, $m = (\kappa_1 - 1) \frac{E}{RT_1}$, where E is the energy of the activation, R the gas constant. Then for the example of a liquid-rocket engine taken in [1], conventionally taking gasoline for heptane, assuming $E = 38$ kcal/mole, $T_1 = 700$, $\alpha = 3$, $\kappa_1 = \kappa_2 = 1.4$, from (6) we get the following evaluation of the critical Mach number $M_{1\ crit} = 0.12$. Within the framework of the real conditions of the working of the liquid-rocket engine, apparently, the rate of the burning will exceed this limit, assuring the inner stability of the system of the burning.

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